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APPLICATION FOR PATENT

CLOCK PROCESSING LOGIC AND METHOD FOR DETERMINING CLOCK SIGNAL CHARACTERISTICS IN REFERENCE VOLTAGE AND TEMPERATURE VARYING ENVIRONMENTS

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CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of commonly-owned U.S. patent application serial number 10/094,101, filed March 8, 2002, which claims priority from commonly owned U.S. provisional application serial number 60/316,399, filed August 31, 2001, and is incorporated herein by this reference.

FIELD OF THE INVENTION

The present invention generally relates to clock signal processing and in particular, to a clock processing logic and method for determining clock signal characteristics in reference voltage and temperature varying environments.

BACKGROUND OF THE INVENTION

Clock processing logic and method for determining clock signal characteristics in reference voltage and temperature varying environments are useful in many applications including those for generating a compensated percent-of-clock period delay signal. The generation of compensated percent-of-clock period delay signals is, in

turn, also useful in many applications. As an example, such a delayed version of a data strobe signal (DQS) is useful for capturing read data (DQ) provided along and edge-aligned with the DQS from a double data rate (DDR) synchronous dynamic random access memory (SDRAM).

The benefits of DDR SDRAMs are well known. Simply put, DDR SDRAMs are probably the most straightforward and least costly approach to doubling memory data bandwidth over the single data rate SDRAMs in common use today.

Read data capture at the memory controller, however, can be a significant challenge using DDR SDRAMs. To assist in read data capture, the DDR SDRAM provides one or more DQS that are edge-aligned with corresponding DQ provided by the DDR SDRAM during a read operation. To capture the data, the memory controller internally delays the received DQS to be within a data valid window, and then captures the DQ using the thus delayed DQS.

The optimal delay for DQS is the average location of the center of the data valid window, taking into account the maximum skew between DQS and DQ (DQSQ") and the reduced data valid window (DV") realized at the memory controller. DQSQ" in this case is the sum of the nominal skew between any data line and its corresponding DQS at the pins of the DDR SDRAM (DQSQ) plus skew additions that are incurred between the DDR SDRAM and the memory controller. For example, in a system where the memory controller is on a separate chip than the DDR SDRAM, such skew additions include board effects between the DDR SDRAM and the chip, and internal routing within the chip. Likewise, DV" in

this case is the nominal DDR SDRAM data valid window at the pins of the DDR SDRAM (DV) reduced by the skew additions.

A percent-of-clock period delay is only one possible approach for implementing the DQS delay for read data capture. Other approaches include using a predetermined absolute delay value or a selectable delay. Each of these implementations, however, is susceptible to process, voltage and temperature variations that may significantly alter the value of their delay line. Such variations may destroy the limited timing budget available for read data capture. Thus, most systems could benefit from a delay implementation that addresses one or more of these error-producing variations.

Delay locked loops (DLLs) have been proposed to compensate for at least reference voltage and temperature variations in the predetermined absolute delay value and selectable delay implementations. A DLL locked to the clock is also thought to be required in a percent-of-clock period delay implementation. However, multiple clock periods are generally required for the DLL to "lock" in these implementations, thereby objectionably adding to the effective read access time in short burst read data captures.

OBJECTS AND SUMMARY OF THE INVENTION

It is an object of the present invention to provide a clock processing logic and method useful for determining clock signal characteristics in reference voltage and temperature varying environments.

Another object is to provide a clock processing logic and method useful for generating a compensated percent-of-clock period delayed signal that compensates for reference voltage and temperature variations.

Still another object is to provide a clock processing logic and method useful for generating a compensated percent-of-clock period delayed signal that is cost effective and simple to implement.

Another object is to provide a clock processing logic and method useful for clock edge detection in a noisy environment.

Yet another object is to provide a clock processing logic and method useful for on-chip measurement of the period of and jitter on a clock signal.

These and additional objects are accomplished by the various aspects of the present invention, wherein briefly stated, one aspect is a clock processing logic for determining an edge of a clock signal indicated in a sample vector by a bit location corresponding to a transition from one or more bits of a first value on one side of the bit location to one or more bits of a second value on another side of the bit location, wherein the bit location varies from cycle to cycle according to reference voltage and temperature variations affecting the clock signal. Included in the clock processing logic are edge detection logic and sensitivity adjustment logic. The edge detection logic is configured to compare adjacent pairs of bits of the sample vector starting from one end of the sample vector to another end of the sample vector until a bit location corresponding to a transition from one or more

bits of a first value on one side of the bit location to one or more bits of a second value on another side of the bit location is detected. The sensitivity adjustment logic is configured to adjust the bit location according to information of at least one other bit location corresponding to a previous cycle of the clock signal that was previously detected by the edge detection logic.

Another aspect of the invention is a method for processing a sample vector indicating an edge of a clock signal by a bit location corresponding to a transition from one or more bits of a first value on one side of the bit location to one or more bits of a second value on another side of the bit location, wherein the bit location varies from cycle to cycle according to reference voltage and temperature variations affecting the clock signal. Included in the method are: detecting a bit location corresponding to a transition from one or more bits of a first value on one side of the bit location to one or more bits of a second value on another side of the bit location; and adjusting the bit location according to information of at least one other bit location corresponding to a previous cycle of the clock signal that was previously detected.

Still another aspect of the invention is a clock processing logic for determining an average clock period and jitter for a clock signal characterized by sample vectors taken on a per cycle basis of the clock signal, wherein individual of the sample vectors indicate at least one edge of the clock signal by a bit location varying from cycle to cycle according to reference voltage and temperature variations affecting the clock signal and corresponding to a transition from one or more bits of a

first value on one side of the bit location to one or more bits of a second value on another side of the bit location. Included in the clock processing logic are an edge filter, sample accumulation logic, and clock period and jitter processing logic. The edge filter is configured to generate filtered sample vectors by marking only bit locations corresponding to edges of a clock signal as indicated in the sample vectors. The sample accumulation logic is configured to generate accumulative sample vectors by logically OR-ing a predefined number of the filtered sample vectors for individual of the accumulative sample vectors. The clock period and jitter processing logic is configured to determine a clock period and jitter on the clock signal for individual of the accumulative sample vectors.

Yet another aspect of the invention is a method for determining an average clock period and jitter for a clock signal characterized by sample vectors taken on a per cycle basis of the clock signal, wherein individual of the sample vectors indicate at least one edge of the clock signal by a bit location varying from cycle to cycle according to reference voltage and temperature variations affecting the clock signal and corresponding to a transition from one or more bits of a first value on one side of the bit location to one or more bits of a second value on another side of the bit location. Included in the method are: generating filtered sample vectors by marking only bit locations corresponding to edges of a clock signal as indicated in the sample vectors; generating accumulative sample vectors by logically OR-ing a predefined number of the filtered sample vectors for individual of the

accumulative sample vectors; and determining a clock period and jitter on the clock signal for individual of the accumulative sample vectors.

Additional objects, features and advantages of the various aspects of the present invention will become apparent from the following description of its preferred embodiment, which description should be taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates, as an example, a first circuit as part of an apparatus for generating a compensated percent-of-clock period delayed signal, utilizing aspects of the present invention.

FIG. 2 illustrates, as an example, a second circuit as part of an apparatus for generating a compensated percent-of-clock period delayed signal, utilizing aspects of the present invention.

FIG. 3 illustrates a block diagram of a first example of a Percent-Of-Clock Period Delay Generator, utilizing aspects of the present invention.

FIG. 4 illustrates a block diagram of a second example of a Percent-Of-Clock Period Delay Generator, utilizing aspects of the present invention.

FIG. 5 illustrates, as an example, a flow diagram of various functions performed by a first embodiment of a Clock Processing Logic, utilizing aspects of the present invention.

FIG. 6 illustrates, as an example, input and output Sample Vectors for a Metastability Filtering

function included in Clock Processing Logic, utilizing aspects of the present invention.

FIG. 7 illustrates, as an example, a flow diagram of a Sensitivity Adjustment function included in Clock Processing Logic, utilizing aspects of the present invention.

FIG. 8 illustrates, as an example, a flow diagram of various functions performed by a second embodiment of a Clock Processing Logic, utilizing aspects of the present invention.

FIG. 9 illustrates, as an example, a logic diagram of a positive edge filter circuit performing a Positive Edge Filtering function included in Clock Processing Logic, utilizing aspects of the present invention.

FIG. 10 illustrates, as an example, a block diagram of a sample accumulator performing a Sample Accumulation function included in Clock Processing Logic, utilizing aspects of the present invention.

FIG. 11 illustrates, as an example, input and output Sample Vectors for a Smoothing Logic function included in Clock Processing Logic, utilizing aspects of the present invention.

FIG. 12 illustrates, as an example, a block diagram of a clock period and jitter processing logic performing the Clock Period and Jitter Processing function of **FIG. 8**, utilizing aspects of the present invention.

FIG. 13 illustrates, as an example, a state transition diagram for a state machine included in the

clock period and jitter processing logic of **FIG. 12**, utilizing aspects of the present invention.

FIG. 14 illustrates, as an example, a flow diagram of various functions performed by a third embodiment of a Clock Processing Logic, utilizing aspects of the present invention.

FIG. 15 illustrates, as an example, a block diagram of a clock period and jitter processing logic performing the Clock Period and Jitter Processing function of **FIG. 14**, utilizing aspects of the present invention.

FIG. 16 illustrates, as an example, a state transition diagram for a state machine included in the clock period and jitter processing logic of **FIG. 15**, utilizing aspects of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 illustrates, as an example, a first circuit **100** as part of an apparatus for generating a compensated percent-of-clock period delayed signal. A first delay tree **110** has (K+1) delay branches **11-0** to **11-K** that are sequentially configured so as to have increasing numbers of serially coupled first delay elements individually of substantially a first delay value D1, so that each of the branches provides incrementally more delay than a previous branch in sequence. In particular, in the first delay tree **110**, a first delay branch **11-0** includes a single delay element **10-0**, a second delay branch **11-1** includes two delay elements **10-0** and **10-1**, a third delay branch **11-2** includes three delay elements **10-0, 10-1**, and

10-2, and so on, down to a (K+1)th delay branch **11-K** that includes K+1 delay elements **10-0** to **10-K**.

A clock signal is provided to each of the delay branches **11-0** to **11-K** through their common delay element **10-0**, to an enable input of a first register **12**, and to a buffer **16**. Outputs of the delay branches **11-0** to **11-K** are coupled to corresponding inputs of the first register **12**. The first register **12** is enabled to capture values on the outputs of the delay branches **11-0** to **11-K** on rising edges of the clock signal. Consequently, a low logic state is captured on the output **13** for each delay branch through which the previous rising and falling edges of the clock signal have passed through when the subsequent rising edge of the clock signal enables the first register **12**; a high logic state is captured on the output **13** for each delay branch through which the previous rising edge of the clock signal has passed through, but the falling edge has not passed through yet when the subsequent rising edge of the clock signal enables the register **12**; and a low logic state is captured on the output **13** for each delay branch through which the previous rising edge of the clock signal has not passed through yet when the subsequent rising edge of the clock signal enables the register **12**. Thus, the output **13** of the first register **12** is indicative of the number of serially coupled delay elements through which a rising edge of the clock signal has passed through during one period of the clock signal.

The delay elements **10-0** to **10-K** are generally sensitive to reference voltage and temperature variations. The clock signal, on the other hand, should be relatively insensitive to such variations. A system clock is

generally capable of providing such a clock signal. As a result of such relative sensitivities between the clock signal and delay elements, the number of serially coupled delay elements through which a rising edge of the clock signal passes through during one period of the clock signal changes with reference voltage and/or temperature variations.

A second register **14** has inputs coupled to corresponding outputs of the first register **12** as in a conventional "pipe-lined" architecture. The second register **14** is also enabled by the clock signal through the buffer **16**. Even if one or more of the output **13** are metastable, inclusion of the second register **14** ensures that the second stage output **15** are all stable (i.e., have all settled down to valid logic states).

The second stage output **15** thus results in a "sample vector" with each of its bit locations representing a "sample" delayed in time from a prior sample (i.e., bit location) by the incremental delay value being added by its corresponding delay branch in the Master Delay Tree circuit **31**. An "edge transition" occurs in the sample vector where the bits change logic states (e.g., change from "0's" on one side of the edge transition to "1's" on the other side, or "1's" on one side of the edge transition to "0's on the other side). A "positive edge transition" in this case, identifies the delay branch (e.g., the last one indicating a "0" or the first one indicating a "1", depending upon which convention is selected), among the delay branches **11-0** to **11-K,** that has approximately the same combined delay from its delay elements as the period of the clock signal. Since each of the delay branches **11-0** to **11-K** also has a

different number of delay elements in it, the positive edge transition also indirectly indicates that number when identifying the branch.

False readings (also referred to herein as "false samples") on one or more of the output **13** and consequently, on corresponding of the output **15** may occur due to the first register **12** latching (also referred to herein as "sampling") certain outputs of the delay branches **11-0** to **11-K** that are metastable. Metastability in this case may result if the value in any one of the delay branches **11-0** to **11-K** is transitioning during the set-up and hold time of the register **12** when it is being enabled. Factors that determine which one of the branches violates such set-up and hold times include the power supply levels, noise, and/or system temperature affecting the value D1 of the delay elements **10-0** to **10-K**, the period of a system clock generating the clock signal being affected by jitter and/or its frequency varying from system to system, or the non-zero rise time of the clock signal.

DQS delay control logic ("DDCL") **17** receives the output **15**, and processes the sample vector provided thereon to determine the correct edge transition in light of possible false samples. It does this by performing two functions on the sample vector.

First, the DDCL **17** locates the earliest positive edge transition in the sample vector. The earliest or first positive edge transition is located in this case, because the sample vector may contain for some reason more than one period of the clock signal. For example, more than one positive edge transition may occur if the combined

delay of the last delay branch **11-K** is greater than a period of the clock signal.

Second, the DDCL **17** compares the position of the newly detected positive edge transition with positions of one or more previously detected positive edge transitions of prior clock periods, and modifies its position as necessary to avoid abrupt adjustment position changes between adjacent clock periods. This function is desirable so that the DDCL **17** provides its output **18** in a manner that adjusts smoothly over time for changes in temperature and/or voltage. In particular, it prevents power supply noise from disrupting valid edge transition detections. The following procedure is one method of performing this second function:

```
if (new_posedge_position<=prev_posedge_position-2)
    posedge_position=prev_posedge_position-1;
else if(new_posedge_position=>prev_posedge_position+2)
    posedge_position=prev_posedge_position+1;
else
    posedge_position=new_posedge_position;
```

The procedure causes the DDCL **17** to change its output **18** smoothly in response to reference voltage and/or temperature variations by adjusting the located position of the positive edge transition in the sample vector at most one position per clock period. The output **18** in this case indicates the position of the positive edge transition on the sample vector. The position of the positive edge transition, in turn, indicates which one of the delay branches **11-0** to **11-K** has a combined delay from its delay elements that most closely approximates the period of the clock signal during a given period of the clock signal at the then prevalent reference voltage and temperature

conditions. Although a threshold value of "2" is used in this example, other values may also be used as determined, for example, by trial-and-error to achieve maximal results.

Alternatively, the second function of the DDCL **17** may be performed using a moving average or other averaging technique. Such techniques would not only avoid abrupt changes of the positive edge transition detected between successive clock periods, but would also prevent "drift" errors that might occur using the prior described technique. As a simple example of a moving average technique, the position of the current positive edge transition may be taken as the average of the current and the nine previously determined positions.

FIG. 2 illustrates, as an example, a second circuit **200** as part of the apparatus for generating a compensated percent-of-clock period delayed signal. A second delay tree **210** has K delay branches **21-0** to **21-K** that are sequentially configured so as to have increasing numbers of serially coupled second delay elements individually of substantially a second delay value D2, so that each of the branches provides incremental more delay than a previous branch in sequence.

The delay branches **21-0** to **21-K** of the second delay tree **210** respectively correspond to the delay branches **11-0** to **11-K** of the first delay tree **110**, so that the ratio of total delay on corresponding branches equal a desired percent-of-clock period. In the present example, where corresponding branches, such as 11-i and 21-i for i=0, 1, ... K, have the same number of delay elements, the percent-of-clock period is equal to the ratio of their respective delay element values. In such case, where the

second delay element D2 has a value that is 20% of that of the first delay element D1, then the percent-of-clock period is also 20%. On the other hand, in another example (not shown), where the first and second delay elements, D1 and D2, are equal in value, then corresponding branches in the first and second delay trees, **110** and **210**, must have different numbers of delay elements in order for the ratio of total delay on the corresponding branches to be equal to the desired percent-of-clock period. In that case, where the percent-of-clock period is desired to be 20%, the number of delay elements in branches of the first delay tree **110** must be five times as many as their corresponding branches in the second delay tree **210**.

A data strobe (DQS) or other signal to be delayed is provided to each of the delay branches **21-0** to **21-K** through their common delay element **20-0**. Outputs of the delay branches **21-0** to **21-K** are coupled to corresponding inputs of a multiplexer **22**, and the output **18** of the DDCL **17** of the first circuit **100** is coupled to a select input of the multiplexer **22**. Consequently, the output of the branch of the second delay tree **210** that corresponds to the branch of the first delay tree **110** is passed through the multiplexer **22** after being selected according to information on the output **18**.

As previously noted, the ratio of total delay on corresponding branches of the first and second delay trees, **110** and **210**, equals the desired percent-of-clock period. Therefore, since the total delay on the branch of the first delay tree **110** has been selected such that its delay is approximately equal to the clock period, the total delay on its corresponding branch of the second delay tree **210** is

approximately the desired percent-of-clock period. As a result, the output signal DQS' on the output of the multiplexer **22** is the desired percent-of-clock period delayed signal.

In brief summary of **FIGS. 1** and **2**, the first circuit **100** determines how many delay elements a clock signal passes through during one period of the clock signal. The second circuit **200** then passes a signal DQS to be delayed through the same number of delay elements according to information received from the first circuit **100**. The ratio of the values of delay elements in the first and second circuits (i.e., D2/D1) determines the percent-of-clock period that the passed signal is delayed. Since the clock signal is relatively insensitive to reference voltage and temperature variations as compared to the delay elements, **10-0** to **10-K** and **20-0** to **20-K**, a reasonably constant percent-of-clock period delay is maintained as more or less delay elements are passed through during each successive period of the clock signal.

FIG. 3 illustrates a block diagram of a first example of a Percent-Of-Clock Period Delay Generator **300** formed by combination of the circuits **100** of **FIG. 1** and **200** of **FIG. 2**. A Master Delay Tree circuit **31** is formed by combination of the first delay tree **110** and the first register **12** of **FIG. 1**, and a Clock Processing Logic circuit ("CPL") **32** is formed by combination of the second register **14** and the DDCL **17** of **FIG. 1**. In this example, both the Master Delay Tree circuit **31** and the CPL **32** are driven by the same clock signal (" CLOCK SIGNAL"), which is preferably the system clock signal.

A Slave Delay Tree circuit **33** is formed by combination of the second delay tree **210** and the multiplexer **22** of **FIG. 2**. As previously described in reference to the operation of the DDCL **17** of **FIG. 1**, the purpose of the CPL **32** is to process the Sample Vector output **13** of the Master Delay Tree circuit **31**, and generate a control signal **18** for the Slave Delay Tree circuit **33** so that a signal DQS provided to the Slave Delay Tree circuit **33** is delayed by the desired percent-of-clock period of the CLOCK SIGNAL to provide output DQS'.

FIG. 4 illustrates a block diagram of a second example of a Percent-Of-Clock Period Delay Generator **400**. In this example, Master and Slave Delay Tree circuits, **31** and **33**, operate and are similarly constructed as their identically referenced counterparts in **FIG. 3**. CPL **42**, however, includes an additional register **421**, which combines with register **422** to provide a double-registering function on a Sample Vector received as output **13** from the Master Delay Tree circuit **31**. The double-registering serves two purposes. First, it increases the time for the Sample Vector (which may be metastable due to race conditions in latching the output **13**) to stabilize. Second, it allows decoupling of the Master Delay Tree circuit **31** and CPL **42** clocks, so that different clock signals may be provided to the Master Delay Tree circuit **31** and the CPL **42**. In particular, in this example, a source clock signal ("SOURCE CLOCK SIGNAL") is provided to the Master Delay Tree circuit **31** while a system clock signal ("SYSTEM CLOCK SIGNAL") is provided to the CPL **42**.

Although the DDCL **423** of the CPL **42** may operate and be similarly constructed as its counterpart DDCL **17** of

FIG. 1, it is preferably different in certain respects so as to provide enhanced edge detection and/or additional functionality such as on-chip clock period and clock jitter measurement. **FIGS. 5~7** illustrate, as an example, details of one such embodiment of the DDCL **423** providing enhanced edge detection, and **FIGS. 8~15** illustrate, as two more examples, details of other embodiments of the DDCL **423** providing additional functionality such as on-chip clock period and clock jitter measurement. In each of these embodiments, the DDCL **423** may be conventionally implemented in hardwired logic, or using a programmed processor, or using a combination of hardwired logic and programmed processor.

FIG. 5 illustrates various functions performed by a first embodiment of the Clock Processor Logic **42**. The DDCL **423**, in this case, provides enhanced edge detection on a double-registered Sample Vector received from the register **422**. Two primary functions performed by the DDCL **423** include a Positive Edge Detection function **52** and a Sensitivity Adjustment function **54**. These functions are generally similar to those described in reference to the operation of the DDCL **17** of **FIG. 1**, with the exception that the Sensitivity Adjustment function **54** is more sophisticated and provides generally enhanced accuracy than the corresponding function described in reference to the DDCL **17** of **FIG. 1**. Other functions such as a Metastability Filtering function **51**, Error Adjustment function **53**, and Manual Override function **55~57** provide additional functionality and flexibility in the edge detection process.

In the Metastability Filtering function **51**, the Sample Vector is processed through a metastability filter which "smoothes" out the Sample Vector. Smoothing of the Sample Vector is desirable, because metastability could cause some bits of the Sample Vector to flip value. An example of the Metastability Filtering function **51** is illustrated in **FIG. 6** wherein a Sample Vector **61**, including false sample bit **617**, is received by the DDCL **423**, and a filtered Sample Vector **62**, including corrected sample bit **627**, is outputted by the DDCL **423**. The false sample bit **617** in this case is a flipped value, because it failed to meet necessary setup and/or hold times when being latched into the register **12** of the Master Delay Tree circuit **41**.

Referring back now to **FIG. 5**, the following algorithm is implemented in the metastability filter performing the Metastability Filtering function **51**:

```
for (i=[FILTERSIZE-1)/2];
     i<BRANCHNUM-(FILTERSIZE+1)/2];
     i=i+1){
     if (FILTERSIZE==3)
          if (in[i-1]+in[i]+in[i+1]>1)
               out[i]=1;
          else
               out[i]-0;
     else
          out[i]=in[i];
}
```

where, "i" is number of the bit location of the Sample Vector being filtered (e.g., ranging from 0 to K); FILTERSIZE = 1 or 3 (wherein "1" implies no filtering in this case); and BRANCHNUM = number of branches in the Master Delay Tree circuit **31** (i.e., K+1). Note that in this and other examples herein, bit location [i] of the

Sample Vector corresponds to delay branch 11-[i] of the Master Delay Tree circuit **31**.

Since the algorithm for the Metastability Filtering function is fully combinational (i.e., no state machines are used in this logic), the Sample Vector can be filtered in a single system clock cycle. The filter size ("FILTERSIZE") is preferably variable so that its value can vary depending on implementation parameters such as the amount of delay per delay element in the Master Delay Tree circuit **31**, the source clock's rise time, the source clock's jitter, and the characteristics of the capturing elements (i.e., flip-flops of register **12**) used in the Master Delay Tree circuit **31**. Accordingly, depending upon such implementation parameters, the filter size may be increased above the 3 bits shown in the example above, or decreased to 1 bit if no filtering is required. The algorithm preferably performs a "majority" function on sets of consecutive bits equal in number to the filter size. In such case, the filter size is preferably an odd number to avoid dead-lock or non-determinative situations. The filter size is stored in a "Filter Size" field ("FS") of a control register (not shown) of the CPL **42**.

In the Positive Edge Detection function **52**, the first positive edge transition in the filtered Sample Vector is determined. As previously described, finding the first positive edge transition (i.e., a first occurrence of a bit of the Sample Vector in ascending branch order that has a "1" value and is immediately followed by one or more bits having a "0" value) in the filtered Sample Vector is equivalent to determining the delay tree branch that has enough delay to cover one period of the SOURCE CLOCK SIGNAL

provided to the Master Delay Tree circuit **31**. Since it is preferable there are enough branches in the Master Delay Tree circuit **31** to cover more than one period of the SOURCE CLOCK SIGNAL (to ensure that at least one period of the SOURCE CLOCK SIGNAL is covered, taking into account reference voltage and temperature variation effects on the SOURCE CLOCK SIGNAL), the filtered Sample Vector may have multiple positive edge transitions. By searching for the first positive edge transition, the DDCL **423** ensures that only one period of the SOURCE CLOCK SIGNAL is used in the percent-of-clock period delay generation.

The following algorithm is implemented in a positive edge detection logic performing the Positive Edge Detection function **52**:

```
        posedgebranch=BRANCHNUM-1;
        for (k=0; k<=(BRANCHNUM-2); k=k+1) {
             if ((in[k]==1)&&(in[k+1]==0)) {
        //Positive edge transition found, check if
   earlier positive edge was found
        if (k<posedgebranch)
        posedgebranch=k; //found earlier positive edge
   transition
        else
             posedgebranch=posedgebranch;
        }
        else posedgebranch=posedgebranch;
        }
```

where, in[k] = bit location [k] of the Sample Vector being input to the positive edge detection logic; and posedgebranch = branch number corresponding to the first positive edge transition in the filtered sample vector.

Since the first positive edge detection algorithm processes the filtered sample vector combinationally, state

machines are not necessarily used. This means that the filtered Sample Vector can be processed in a single system clock cycle.

In the Error Adjustment function **53**, an error adjustment is applied to the first positive edge transition. The error adjustment is a plus or minus delay value that is effectuated by adjusting the first positive edge transition to a different branch of the Master Delay Tree circuit **31** than the one determined in by the First Positive Edge function **52**. The error adjustment is based on a value programmed in an "Error Adjustment or Offset" field ("EO") of a control register (not shown) of the CPL **42**. This feature allows correction of known errors in the generation of the percent-of-clock period delayed signal DQS'.

If value other than zero is programmed in the EO field, the Error Adjustment function **53** offsets the first positive edge transition detected by the First Positive Edge function **52** by a number of branches corresponding to the programmed value. For example, a programmed value of 2 will result in moving the first positive edge transition two branches in a positive direction (e.g., from branch 11-n to branch 11-[n+2]), and a programmed value of -2 will result in moving the first positive edge transition two branches in a negative direction (e.g., from branch 11-n to branch 11-[n-2]). Preferably, the programmed value is 2's complement encoded and in the range of -16 to +15 for a 32-bit Sample Vector. Regardless of the value programmed in the EO field, use of the Error Adjustment function **32** does not disable any other functions of the DDCL **423**. Thus, all the advantages of using the Percent-Of-Clock Period Delay

Generator **400** (e.g., dynamic temperature adjustment, dynamic voltage adjustment, etc.) are preserved.

Use of the Error Adjustment function **53** assumes that a user is aware of an error in the generation of the delayed signal DQS' generated by the Percent-Of-Clock Period Delay Generator **400**. In the case in which the Percent-Of-Clock Period Delay Generator **400** is used in a DDR controller, this assumption is reasonable as the signal to be delayed is used to capture data read from the DDR SDRAM. If the value of the data read is erroneous and the user suspects that the Percent-Of-Clock Period Delay Generator **400** has a problem, the user may iteratively program the EO field and read data from the DDR SDRAM until correct data is captured.

In the Sensitivity Adjustment function **54**, the position of the newly determined first positive edge transition is compared with positions of one or more previously determined first positive edge transitions of prior clock periods, and modified according to predefined rules so as to avoid abrupt position changes between adjacent clock periods. In particular, this function controls how sensitive the Percent-Of-Clock Period Delay Generator **400** is to temperature, voltage, source clock jitter, and source clock frequency changes. The "sensitivity" of the Percent-Of-Clock Period Delay Generator **400** is programmed through an "Adjustment Sensitivity" ("AS") field in a control register (not shown) of the CPL **42**, and the sensitivity period of the Percent-Of-Clock Period Delay Generator **400** is programmed through a "Sensitivity Period" ("SP") field of a control register (not shown) of the CPL **42**.

FIG. 7 illustrates a flow diagram describing the operation of sensitivity adjustment logic performing the Sensitivity Adjustment function **54**. Each clock cycle, the sensitivity adjustment logic included in the DDCL **423** determines which branch of the Master Delay Tree circuit **31** corresponds to a period of the source clock signal and provides an output **18** indicating the corresponding branch of the Slave Delay Tree circuit **33** to be used to delay the signal DQS by the predefined percent-of-clock period delay. The output **18** in this case is encoded to indicate the slave delay tree branch by serving as a select input to the MUX **22** of the Slave Delay Tree Circuit **33**.

Following are five conditions A~E implemented in the sensitivity adjustment logic to determine the Next Branch ("B(t+1}") of the Slave Delay Tree circuit **33** to be indicated by the output **18**, based upon the Current Branch ("B(t)") of the Slave Delay Tree circuit **33** being indicated by the output **18**. In the following, the term "Error Adjusted Branch" is the output of the Error Adjustment function **53**, the term "BRANCHNUM" is the number of branches of the Slave Delay Tree circuit **33** (which is also equal to the number of branches of the Master Delay Tree circuit **31**), the symbol "<" means less than, the symbol ">" means greater than, the symbol "==" means equal, and the symbol "!=" means not equal:

<u>Condition A</u>: [Error Adjusted Branch < (Current Branch - AS)] && [Current Branch > AS].

<u>Condition B</u>: [Error Adjusted Branch > (Current Branch + AS)] && [(BRANCHNUM - AS) > Current Branch].

Condition C: (Sensitivity Counter == SP).

Condition D: [Error Adjusted Branch < Current Branch] && [Current Branch != 0].

Condition E: [Error Adjusted Branch > Current Branch] && [Current Branch != BRANCHNUM - 1].

Now referring to **FIG. 7**, in **541**, if Condition A is satisfied, then in **71**, the Next Branch number is determined by decrementing the Current Branch number by one. Note that Condition A in this case is only satisfied if: (i) the Error Adjusted Branch number is less than the Current Branch number, (ii) the difference between the Current Branch number and the Error Adjusted Branch number is greater than the programmed value ("AS") of the AS field, and (iii) the Current Branch number is greater than AS. Thus, abrupt changes in the Next Branch number is avoided by only decrementing the Current Branch number by at most one rather than making the Next Branch number equal to the Error Adjusted Branch number when the Current Branch number is greater than the Error Adjusted Branch number by more than AS.

If Condition A is not satisfied, however, then in **542**, it is next determined whether Condition B is satisfied. If Condition B is satisfied, then in **72**, the Next Branch number is the determined by incrementing the Current Branch number by one. Note that Condition B in this case is only satisfied if: (i) the Error Adjusted Branch number is greater than the Current Branch number, (ii) the difference between the Error Adjusted Branch number and the Current Branch number is greater than AS,

and (iii) the Current Branch number is less than the branch number corresponding to (BRANCHNUM - AS). Thus, abrupt changes in the Next Branch number are avoided by only incrementing the Current Branch number by at most one rather than making the Next Branch number equal to the Error Adjusted Branch number when the Error Adjusted Branch number is greater than the Current Branch number by more than AS.

If Condition B is not satisfied, then the magnitude of the difference between the Error Adjusted Branch number and the Current Branch number is less than or equal to AS. In this case, if Condition C is not satisfied in **543**, then in **73**, the Next Branch number is determined to be the same as the Current Branch number. Note that Condition C in this case is only satisfied if a Sensitivity Counter (not shown) in the CPL **42** has counted up to the programmed value ("SP") of the SP field. Each system clock cycle, the Sensitivity Counter increments its count by one, until the count reaches the value of SP, at which time, it stops at that count until reset. The Sensitivity Counter resets to zero when any one of the following events occur: (i) the CPL **42** is disabled, (ii) the Error Adjusted Branch number equals the Current Branch number, or (iii) Condition C is satisfied.

If Condition C is satisfied, then the Sensitivity Counter is reset and in **544**, a determination is made whether Condition D is satisfied. If Condition D is satisfied, then in **74**, the Next Branch number is determined by decrementing the Current Branch number by one. Note that Condition D in this case is only satisfied if: (i) the Error Adjusted Branch number is less than the Current

Branch number, and (ii) the Current Branch number does not equal the lowest branch number (e.g., 0 in this example). Thus, if the difference between the Current Branch number and the Error Adjusted Branch number is less than or equal to AS, and has remained in that relationship for a period of time sufficient to allow the Sensitivity Counter to count to SP, then the Next Branch number is determined to be the Current Branch number decremented by one (unless the Current Branch number corresponds to the lowest branch in the Slave Delay Tree circuit **33**).

If Condition D is not satisfied, then in **545**, it is determined whether Condition E is satisfied. If Condition E is satisfied, then in **75**, the Next Branch number is determined by incrementing the Current Branch number by one. On the other hand, if Condition E is not satisfied, then in **76**, the Next Branch number is determined to be equal to the Current Branch number. Note that Condition E in this case is only satisfied if: (i) the Error Adjusted Branch number is greater than the Current Branch number, and (ii) the Current Branch number does not equal the highest branch number (e.g., BRANCHNUM equals one more than the highest branch number since the first branch number is labeled "0" in this example). Thus, if the difference between the Error Adjusted Branch number and the Current Branch number is less than or equal to AS, and has remained in that relationship for a period of time sufficient to allow the Sensitivity Counter to count to SP, then the Next Branch number is determined to be the Current Branch number incremented by one (unless the Current Branch number corresponds to the highest branch in the Slave Delay Tree circuit **33**).

Referring back now to **FIG. 5**, in the Manual Override function **55~57**, the branch number of the Slave Delay Tree circuit **33** determined by the Percent-Of-Period Delay Generator **400** using functions **51~54** as described above, can be overridden and replaced by a user programmable value. To perform such manual override, an Enable bit ("EN") in a control register (not shown) that is preferably included in the CPL **42** is cleared, and a Branch Select field ("BS") of a control register (not shown) that is also preferably included in the CPL **42** is programmed with a branch number. The value programmed in the BS field is preferably a value between 0 and (BRANCHNUM-1), which range covers all branches of the Slave Delay Tree circuit **33**. This function is useful, among other reasons, for testing purposes as it provides a way for the user to check signal delaying across all branches of the Slave Delay Tree circuit **33**. Also, it provides a useful safeguard in case of malfunction of the Percent-Of-Clock Period Delay Generator **400**.

In **55**, the EN bit is checked to determine whether a manual override of the Percent-Of-Clock Period Delay Generator **400** is in effect. If the EN bit is found to have been cleared, then in **57**, branch number is read from the BS field and that branch number is properly encoded and provided as the control signal **18** to the Slave Delay Tree circuit **33** instead of the branch number determined through **51~54** as described above. On the other hand, if the EN bit has not been cleared, then in **56**, the branch number that was determined through **51~54** is properly encoded and provided as the control signal **18** to the Slave Delay Tree circuit **33**.

Although the Manual Override function **55~57** is shown as occurring after **51~54**, it should be readily apparent that it could also occur before **51~54**. In such a case, the Manual Override function may disable or turn-off the SYSTEM CLOCK SIGNAL to the CPL **42** and provide the control signal **18** directly to the Slave Delay Tree circuit **33**. Turning off the SYSTEM CLOCK SIGNAL in this case would likely reduce the power consumed by the Percent-Of-Clock Period Delay Generator **400**.

FIG. 8 illustrates various functions performed by a second embodiment of the Clock Processing Logic **42**. The DDCL **423** in this case provides enhanced edge detection and additional functionality such as on-chip clock period and clock jitter measurement after receiving the double-registered sample vector from register **422**. This embodiment has the advantage of higher result accuracy, lower gate count, and better scalability (i.e., the gate count does not increase as much when branches are added to the Master Delay Tree circuit **31**) relative to the first embodiment of the CPL **42** as described in reference to **FIGS. 5~7**. On the other hand, such advantages are achieved at the expense of higher computational latency relative to the first embodiment. In many applications, however, such higher computational latency is acceptable.

In the Metastability Filtering function **81**, the Sample Vector is processed in the same manner as described in reference to the Metastability Filtering function **51** of **FIG. 5**. The resulting filtered Sample Vector is generally characterized by a first negative edge transition (i.e., the first occurrence starting with the bit location corresponding to delay branch 11-0 in the filtered Sample

Vector of one or more "0" bits followed by one or more "1" bits) indicating the falling edge of the SOURCE CLOCK SIGNAL, and a first positive edge transition (i.e., the first occurrence starting with the bit location corresponding to delay branch 11-0 in the filtered Sample Vector of one or more "1" bits followed by one or more "0" bits) indicating the corresponding rising edge of the SOURCE CLOCK SIGNAL. Multiple negative and positive edge transitions may occur in the filtered Sample Vector if the total delay of the Master Delay Tree circuit **31** is significantly greater than the SOURCE CLOCK SIGNAL period.

In the Positive Edge Filtering function **82**, the filtered Sample Vector is processed so that only positive edge transitions are marked in the resulting Sample Vector. **FIG. 9** illustrates an example of a positive edge filter **510** used in performing the Positive Edge Filtering function **82**. In this example, the positive edge filter **510** includes an Exclusive-OR gate **511** and an AND gate **512** that are coupled together so that their output OUT[X] equals "1" only if input IN[X} equals "1" and input IN[X+1] equals "0", where X and [X+1] are a pair of consecutive bit locations in both the Sample Vectors **91** and **92**. For example, if bits **918** (value = "1") and **919** (value = "0") of the filtered Sample Vector **91** are respectively coupled to IN[X] AND IN[X+1], then OUT[X] equals "1", which value is provided as bit **928** of the resulting Sample Vector **92**.

Any other combination of input values for IN[X] and IN[X+1] results in output OUT[X] equaling "0". For example, if bits **910** (value = "0") and **911** (value = "0") of the filtered Sample Vector **91** are respectively coupled to IN[X] AND IN[X+1], then OUT[X] equals "0", which value is

provided as bit **920** of the resulting Sample Vector **92.** Likewise, if bits **911** (value = "0") and **912** (value = "1") of the filtered Sample Vector **91** are respectively coupled to IN[X] AND IN[X+1], then OUT[X] equals "0", which value is provided as bit **921** of the resulting Sample Vector **92.** Further, if bits **917** (value = "1") and **918** (value = "1") of the filtered Sample Vector **91** are respectively coupled to IN[X] AND IN[X+1], then OUT[X] equals "0", which value is provided as bit **927** of the resulting Sample Vector **92.**

Thus, wherever a positive edge transition occurs in the filtered Sample Vector **91,** the positive edge transition is marked as a "1" in the corresponding bit location of the resulting Sample Vector **92.** If multiple positive edge transitions occur in the filtered Sample Vector due to the total delay of the Master Delay Tree circuit **31** being multiple times longer than the period of the SOURCE CLOCK SIGNAL, then multiple of such positive edge transitions are marked as "1" in their corresponding bit locations of the resulting Sample Vector **92.**

Although only one positive edge filter **510** is shown and described in reference to **FIG. 9,** it is to be appreciated that in a hard-wired logic implementation of the Positive Edge Filtering function **82,** there may be a number of such positive edge filters that is equal to or one less than the number of bits in the filtered Sample Vector **91.** For example, where there are N bits in the Sample Vector, the 1^{st} through [N-1] bits of the filtered Sample Vector **91** may be coupled to respective first inputs IN[X] of (N-1) positive edge filters while the 2^{nd} through N bits of the filtered Sample Vector **91** are coupled to respective second inputs IN[X+1] of the (N-1) positive edge

filters. Outputs OUT[X] of the (N-1) positive edge filters provide in such case provide values for the 1^{st} through [N-1] bit locations of the resulting Sample Vector **92.** The value for the N^{th} bit location in this case is set to "0".

Referring back to **FIG. 8,** in the Sample Accumulation function **83,** a predefined number of filtered Sample Vectors generated by the Positive Edge Filtering function **82** are logically OR-ed together to generate an accumulative Sample Vector. The number of filtered Sample Vectors being OR-ed together (i.e., being accumulated) in this case is determined by a value stored in an Accumulated Cycles ("AC") field of a control register (not shown) that is preferably included in the CPL **42.** The resulting pattern of marked bits in the accumulative Sample Vector represents a sampled imprint of jitter on the SOURCE CLOCK SIGNAL over a period of time determined by the number of cycles of the SYSTEM CLOCK SIGNAL as specified in the AC field.

An example of one implementation of the Sample Accumulation function **83** is illustrated in **FIG. 10.** A sample accumulator **1000** (performing the Sample Accumulation function **83**) includes an accumulation register **1010,** a number of OR gates (such as OR gate **1020**), control logic **1030,** and an accumulation counter **1040.** The number of OR gates equals the number of bit locations in the Sample Vectors received from the Positive Edge Filtering function **82** as well as those generated by the Sample Accumulation function **83.** Each of the OR gates is coupled to a corresponding bit location of the accumulation register **1010** so that a previously stored Sample Vector is logically OR-ed with a newly received Sample Vector (such as Sample

Vector **92**) from the Positive Edge Filtering function **82**, and the resulting Sample Vector (i.e., outputs of the OR gates) are then stored in the accumulation register **1010** under control of the control logic **1030**. Upon receiving a start indication ("START_ACCUM"), the control logic **1030** resets the accumulation register **1010** (e.g., so that all bit locations contain a "0"). The control logic **1030** then causes the outputs of the OR gates to be latched into the accumulation register **1010** each cycle to accumulate Sample Vectors until it receives an indication from the accumulation counter **1040** that the number of cycles has reached the value stored in the AC field. Upon receiving such indication, the control logic **1030** then stops accumulating Sample Vectors, and an accumulation done indication ("ACCUM_DONE") is generated. The accumulation counter **1040** starts counting after the Sample Accumulator **1000** receives the start indication, and stops counting after counting to the AC value stored in AC field. After receiving the start indication ("START_ACCUM"), the accumulation counter **1040** first resets its count back to zero, then starts counting clock cycles of the SYSTEM CLOCK SIGNAL. When the count of the accumulation counter **1040** reaches the AC value, it then generates the indication that the number of cycles has reached the AC value, and waits until receiving another start indication.

In the Smoothing Logic function **84**, gaps or "0's" , if present, in patterns of "1's" in the accumulated Sample Vector are eliminated in order to condition the accumulated Sample Vector for subsequent processing by the Clock Period and Jitter Processing function **85**. Gaps may occur, because jitter is unpredictable and further, only a

finite number of samples are being taken in the Sample Vector. The Smoothing Logic function **84** is implemented, for example, by the algorithm described in reference to the Metastability Filtering function **51** of **FIG. 5.** As illustrated in **FIG. 11,** after processing by the Smoothing Logic function **84,** a gap (i.e., a "0" in a pattern of "1's") in bit location **1007** of the accumulation register **1010** (as shown in the register on the left of the smoothing logic **1100**) is "eliminated" by storing a "1" value in the corresponding bit location **1107** of a temporary register **1110** while copying values stored in all other bit locations (e.g., 10xx) of the accumulation register **1010** into corresponding bit locations (e.g., 11xx) of the temporary register **1110** (as shown in the register on the right of the smoothing logic **1100**). The contents of the temporary register **1110** are then used instead of those of the accumulation register **1010** for subsequently processing by the Clock Period and Jitter Processing function **85.**

In the Clock Period and Jitter Processing function **85,** average clock periods and measurements of jitter on the SOURCE CLOCK SIGNAL are determined from accumulative Sample Vectors that have been processed by the Smoothing Logic function **84. FIG. 12** illustrates, as an example, a clock period and jitter processing logic **1200** that performs the Clock Period and Jitter Processing function **85** on the accumulated Sample Vectors. Included in the clock period and jitter processing logic **1200** are a finite state machine **1201,** a counter **1202,** a first statistics register ("REG A") **1203,** a second statistics register ("REG B"), a processor **1205,** and a shift register **1210.**

Operation of the finite state machine **1201** is illustrated in **FIG. 13**. In **1301**, the finite state machine **1201** continuously checks the enable bit ("EN") described in reference to the Manual Override function **55~57** of **FIG. 5**, that indicates that the CPL **42** is enabled. If the CPL **42** is found to be enabled, then in **1302**, the state machine **1201** pulses or otherwise activates the START_ACCUM signal that is provided to the Sample Accumulation function **83**. The state machine **1201** then waits until it detects an assertion of or other activation indication on the ACCUM_DONE signal being received from the Sample Accumulation function **83**, which indicates that an accumulated Sample Vector is ready for processing.

Once the state machine **1201** detects that the ACCUM_DONE signal has been asserted, in **1303**, the state machine **1201** copies or otherwise transfers the accumulated Sample Vector that is ready for processing in the temporary register **1110** to a shift register **1210**. The state machine **1201** also pulses the START_ACCUM signal again at this time so that the Sample Accumulation function **83** generates another accumulated Sample Vector while the contents of the shift register **1210** are being processed. Additionally, a counter **1202** is enabled and initialized to a value that corresponds to the number of delay elements in the first delay branch (i.e., branch **11-0**) of the Master Delay Tree circuit **31**. The counter **1202** is initialized to this value, because in some implementations of the Master Delay Tree circuit **31**, it is possible that the first delay branch may have more delay elements than subsequent branches (i.e., branches **11-1** to **11-K**). Initializing the counter **1202** to this value consequently accounts for these additional delay

elements in such cases for the subsequent calculation of the clock period for the SOURCE CLOCK SIGNAL.

In **1304**, starting with the first bit location of the shift register **1210** (corresponding to the first delay branch of the Master Delay Tree circuit **31**), the contents of the shift register **1210** are read out at the rate of one bit location per system clock cycle. Meanwhile, the counter **1202** also counts at the same rate starting with the reading of the first bit location of the shift register **1210** by the state machine **1201**. The state machine **1201** reads the contents of each bit location until it finds a value of "1" stored in a bit location. Once a value of "1" is found, the count of the counter **1202** is transferred to the second statistics register ("REG B") **1204**, and the count of the counter **1202** is reset to zero and the counter **1202** is re-enabled in order to continue counting.

In **1305**, the state machine **1201** then continues reading the contents of bit locations of the shift register **1210** until it finds a value of "0" stored in a bit location. Once a value of "0" is found, the state machine **1201** then transfers the count of the counter **1202** to the first statistics register ("REG A") **1203**, and checks whether the ACCUM_DONE signal is being asserted again to indicate that a next accumulated Sample Vector is ready for processing. If the ACCUM_DONE signal is being so asserted, then the state machine **1201** jumps back to **1303** to start processing the next accumulated Sample Vector. On the other hand, if the ACCUM_DONE signal is not being so asserted at that time, then in **1306**, the state machine **1201** waits until it detects such assertion. When the state machine **1201** does detect a next assertion of the ACCUM_DONE

signal, it jumps back to **1303** to start processing the next accumulated Sample Vector.

Each time the state machine **1201** has loaded the statistics registers **1203** and **1204** with the counts from the counter **1202** as described in reference to **1304** and **1305** above, the processor **1205** calculates an average clock period and jitter from those count values. In particular, the source clock period is determined by adding one-half of the count value stored in the first register ("REG A") **1203** to the count value stored in the second register ("REG B") **1204** to determine the delay branch of the Master Delay Tree circuit **31** whose total delay time most closely matches the average period of the SOURCE CLOCK SIGNAL provided to the Master Delay Tree circuit **31** during the time of the accumulative Sample Vectors. For example, if a count of 5 has been stored in both statistics registers **1203** and **1204,** then either the seventh or eighth delay branch would be selected since the calculation results in a value of seven and one-half. To effectuate dividing the bit value in the first statistics register **1203** by two, the bit values in the first statistics register **1203** are simply shifted one bit to the right. This technique saves gate count by eliminating the need for a logic divider to perform the division.

The source clock jitter, on the other hand, is simply determined by reading the count value stored in the first statistics register ("REG A") **1203.** For example, if a count value of 5 has been stored in the first statistics register **1203,** then the total delay time of the fifth delay branch of the Master Delay Tree circuit **31** is determined to

be approximately equal to the amount of the jitter on the SOURCE CLOCK SIGNAL.

The average source clock calculated from the count values by the Clock Period and Jitter Processing function **85** is considered a more accurate indication of the first positive edge transition than that determined by the Positive Edge Detection function **52** of **FIG. 5,** since the delay branch corresponding to the average source clock period's count value is determined using information obtained over several clock cycles instead of just one.

In the Error Adjustment function **86,** an error adjustment is applied to the source clock period's corresponding delay branch of the Master Delay Tree circuit **31,** in the same manner as described in reference to the Error Adjustment function **53** of **FIG. 5.** Likewise, the Manual Override function **87** may be applied in the same manner as described in reference to the Manual Override function **55~57** of **FIG. 5.** Although a Sensitivity Adjustment function could also be applied such as that described in reference to the Sensitivity Adjustment function **54** of **FIG. 5,** it is not included in this case, because the Clock Period and Jitter Processing function **85** already performs an averaging operation through its source clock period calculation.

After determining the delay branch of the Master Delay Tree circuit **31** that has the same or most nearly the same total delay as the period of the SOURCE CLOCK SIGNAL provided to the Master Delay Tree circuit **31,** the number of that delay branch is encoded as appropriate and provided as output **18** of the CPL **42** to the Slave Delay Tree circuit **33.** The Slave Delay Tree circuit **33** then delays a signal DQS so

as to generate the desired percent-of-clock period delay signal DQS'.

FIG. 14 illustrates various functions performed by a third embodiment of the Clock Processing Logic **42**. This embodiment primarily differs from the second embodiment described in reference to **FIGS. 8~13** by eliminating the Smoothing Logic function **84** of **FIG. 8** and replacing the Clock Period and Jitter Processing function **85** of **FIG. 8** with the Clock Period and Jitter Processing function **144** of **FIG. 14**, as further described in reference to **FIGS. 15~16**. Functions **141, 142, 143, 145** and **146** of this third embodiment of the Clock Processing Logic **42** operate as their respective counterparts **81, 82, 83, 86,** and **87** in the second embodiment of the Clock Processing Logic **42** as previously described in reference to **FIGS 8~10**.

FIG. 15 illustrates a block diagram of a clock period and jitter processing logic **1500** that performs the Clock Period and Jitter Processing function **144** on Accumulated Sample Vectors. Included in the clock period and jitter processing logic **1500** are a finite state machine **1501**, a period counter ("P CNTR") **1502**, a jitter counter ("J CNTR") **1506**, a gap counter ("G CNTR") **1507**, a first statistics register ("REG A") **1503**, a second statistics register ("REG B") **1504**, a processor **1505**, and a shift register **1510**.

Operation of the finite state machine **1601** is illustrated in **FIG. 16**. States **1601** and **1602** of **FIG. 16** operate identically as respectively corresponding states **1301** and **1302** of **FIG. 13**.

In **1603**, the state machine **1501** copies or otherwise transfers the accumulated Sample Vector that is ready for processing in the temporary register **1110** to the shift register **1510**. The state machine **1501** also pulses the START_ACCUM signal (e.g., pulls it high to a value "1") so that the Sample Accumulation function **143** generates another accumulated Sample Vector while the contents of the shift register **1510** are being processed. The state machine **1501** also initializes the period counter **1502** to a value that corresponds to the number of delay elements in the first delay branch of the Master Delay Tree circuit **31**. The state machine **1501** also resets the jitter counter **1506**, the gap counter **1507**, and the first and second statistics registers **1503** and **1504** to zero values.

In **1604**, starting with the first bit location (corresponding to the first delay branch of the Master Delay Tree circuit **31**) of the shift register **1510**, the contents of the shift register **1510** are read out at the rate of one bit location per system clock cycle. Meanwhile, the state machine **1501** enables the period counter **1502** so that it is also counting at the same rate starting with the reading of the first bit location of the shift register **1510** by the state machine **1501**. The state machine **1501** then reads the contents of each bit location until it finds a value of "1" stored in a bit location. Once a value of "1" is found, the state machine **1501** halts the period counter **1502**, and causes its then current count to be copied to the second statistics register ("REG B") **1504**.

In **1605**, the state machine **1501** enables the jitter counter **1506**, and continues reading contents of the

shift register **1510** until it finds a value of "0" stored in a bit location. Once a value of "0" is found, the state machine **1501** causes the then current count of the jitter counter **1506** to be copied to the first statistics register ("REG A") **1503**. The jitter counter **1506** is allowed to continue counting, however.

In **1606**, the state machine **1501** enables the gap counter **1507**, and continues reading contents of the shift register **1510** until either it finds a value of "1" stored in a bit location or it counts up to a limit value such as one-half of the count stored in the second status register ("REG B") **1504** (i.e., a limit value equivalent to a count that corresponds to one half of the low end of the SOURCE CLOCK SIGNAL with jitter).

If the gap counter **1507** does not find a value of "1" before reaching the limit value, then the state machine **1501** checks whether the ACCUM_DONE signal is being asserted again at that time to indicate that a next accumulated Sample Vector is ready for processing. If the ACCUM_DONE signal is being asserted, then the state machine **1501** returns to **1603** to process the next accumulated Sample Vector. If the ACCUM_DONE signal is not being asserted, however, then in **1607**, the state machine **1501** waits until it detects such assertion. When the state machine **1501** does detect a next assertion of the ACCUM_DONE signal, it returns to **1603** to process the next accumulated Sample Vector.

On the other hand, if the gap counter **1507** does find a value of "1" stored in a bit location before reaching the limit value in **1606**, then the state machine

1501 resets the gap counter **1507** to zero, and jumps back to **1605**.

Calculations for the period and jitter are then performed by the processor **1505** in the same fashion as described in reference to the processor **1205** of **FIG. 12**.

Information of the source clock period and jitter as determined by the Clock Period and Jitter Processing function **85** of **FIG. 8** or **144** of **FIG. 14** may also be useful for other applications other than generating a percent-of-clock period delay signal within the same system as the Percent-of-Clock Period Delay Generator **400**. In such case, such information of the source clock period and jitter are stored in appropriate registers accessible to a Central Processing Unit (not shown) in the system.

One particular advantage of the Clock Processing Logic **42** is that it is conducive to on-chip measurement of clock or other digital signal edge characteristics in a voltage and/or temperature varying environment. In particular, the embodiments of the Clock Processing Logic **42** described in reference to **FIGS. 8~16** are capable of performing clock period and jitter measurement of an on-chip clock and make those measurements available to off-chip resources through registers storing the measurement information. Such a capability is particularly useful in situations where on-chip clocks need to be characterized and their signals cannot be readily provided off-chip due to pin-count or frequency restrictions on the chip's input/output pad circuitry. It is also useful even where on-chip signals can be provided off-chip, because it eliminates the need for expensive equipment to perform such measurements, the time consumed in setting such equipment

up, and the inconvenience of ensuring that such testing be done in a proper test environment.

It is noteworthy that the clock period may be estimated by multiplying the nominal delay value of a delay element by the number of delay elements in the delay branch of the Master Delay Tree circuit **31** that has been determined to have the same or most nearly the same total delay as the period of the SOURCE CLOCK SIGNAL provided to the Master Delay Tree circuit **31**. The nominal delay value for such calculation is preferably determined by taking into account (i.e., correlating) the process, temperature and reference voltage conditions under which the clock period is being estimated against pre-calculated delay values for different processes, temperatures, and reference voltages.

Although the various aspects of the present invention have been described with respect to a preferred embodiment, it will be understood that the invention is entitled to full protection within the full scope of the appended claims.